

The 24-Hour Night Shift: Astronomy from Microlensing Monitoring Networks

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Abstract. Scores of on-going microlensing events are now announced yearly by the microlensing discovery teams OGLE, MACHO and EROS. These early warning systems have allowed other international microlensing networks to focus considerable resources on intense photometric — and occasionally spectroscopic — monitoring of microlensing events. Early results include: metallicity measurements of main sequence Galactic bulge stars; limb darkening determinations for stars in the Bulge and Small Magellanic Cloud; proper motion measurements that constrain microlens identity; and constraints on Jovian-mass planets orbiting (presumably stellar) lenses. These results and auxiliary science such as variable star studies and optical identification of gamma ray bursts are reviewed.

1. Introduction

Since the first Galactic events were announced (Alcock et al. 1993; Aubourg et al. 1993; Udalski et al. 1993), microlensing has developed from an odd curiosity to a versatile astronomical tool. Over the past 6 years, MACHO, OGLE and EROS have found hundreds of rare microlensing events in the dense stellar fields of the Galactic bulge and Magellanic Clouds — a task truly akin to finding needles in the proverbial haystack. Much of the progress that has been made in microlensing can be attributed to the ability and willingness of the discovery teams to provide public alerts of on-going microlensing events, allowing other resources to be dedicated to intense monitoring of large numbers of events. The additional astronomy derived from this often round-the-clock monitoring forms the subject of my brief review. A more general discussion of microlensing can be found in the review by Mao (1999).

The scientific goals and capabilities of microlensing *discovery teams* and microlensing *monitoring teams* are quite different. The observational motivation of microlensing discovery projects is the search for very rare events lasting on the order of weeks to months, with the primary goal of understanding their relationship to the (dark and luminous) mass budget of the Galaxy. To this end, discovery teams (EROS II, MACHO, MOA, and OGLE II) must photometer huge numbers ($\sim 10^7$) of stars every 1–3 nights, using wide field (~ 1 square deg) detectors on single, dedicated telescopes in Chile, Australia and New Zealand.

In contrast, the goal of intense monitoring networks is the detection and characterization of higher order perturbations — or anomalies — atop the primary microlensing signature. Since these anomalies are often weak and of short

duration, high photometric precision and dense temporal sampling are required. To meet this challenge, international collaborations have built worldwide networks capable of precise, \sim hourly, round-the-clock monitoring. The current capabilities of these networks are summarized in Table 1.

Table 1. 1999 Status of Microlensing Monitoring Teams^a

Team	Telescope(s)	Time Allotment	Seeing	Pixel Size
GMAN ^b	MSSSO 0.76m, Australia	2 hrs/night	2.3''	0.36''
	CTIO 0.9m, Chile	1.5 hrs/night	1.3''	0.40''
	Wise 1.0, Israel	1 obs/night	2.0''	0.70''
MOA ^c	Mt. John 0.6m, New Zealand	20 nights/year	2.5''	0.81''
MPS ^d	MSSSO 1.9m, Australia	\sim 8 weeks/year	2.3''	—
PLANET ^e	SAAO 1.0m, South Africa	100% Bulge Season	1.6''	0.31''
	YALO 1.0m, Chile	75% Bulge Season	1.5''	0.30''
	Canopus 1.0m, Tasmania	90% Bulge Season	2.3''	0.44''
	Perth 0.6m, W. Australia	75% Bulge Season	2.0''	0.58''

^aMost teams expect improvements in capability and/or time allocations in 2000; GMAN plans to stop normal operations at the end of the 1999 calendar year.

^bGMAN Alert Homepage: <http://darkstar.astro.washington.edu>

^cMOA Homepage: <http://www.phys.vuw.ac.nz/dept/projects/moa>

^dMPS Homepage: <http://bustard.phys.nd.edu/MPS>

^ePLANET Homepage: <http://www.astro.rug.nl/~planet>

Due to the excellent real-time search and alert facilities of the discovery teams, intense monitoring networks can be productive continuously, typically following \sim 10 events at any given time during the prolific Galactic bulge season. Because the location of the event is known, large detectors are not critical to the monitoring networks; more important is good image quality to ensure high photometric precision in dense microlensing fields. Due to the high temporal sampling rates required for anomaly detection, monitoring teams typically photograph $\mathcal{O}(100)$ fewer stars $\mathcal{O}(20)$ times more frequently with $\mathcal{O}(2)$ times better precision than do the discovery teams over the course of an observing season.

2. Science of Intense Microlensing Monitoring

Intense microlensing monitoring science falls into three broad categories: (1) using microlensing as a large aperture, high-resolution telescope to study the background sources, (2) characterizing anomalies in the light curve (or spectrum) of the background source to learn about the lensing system, (3) auxiliary science from simultaneous monitoring or unrelated time-critical photometry.

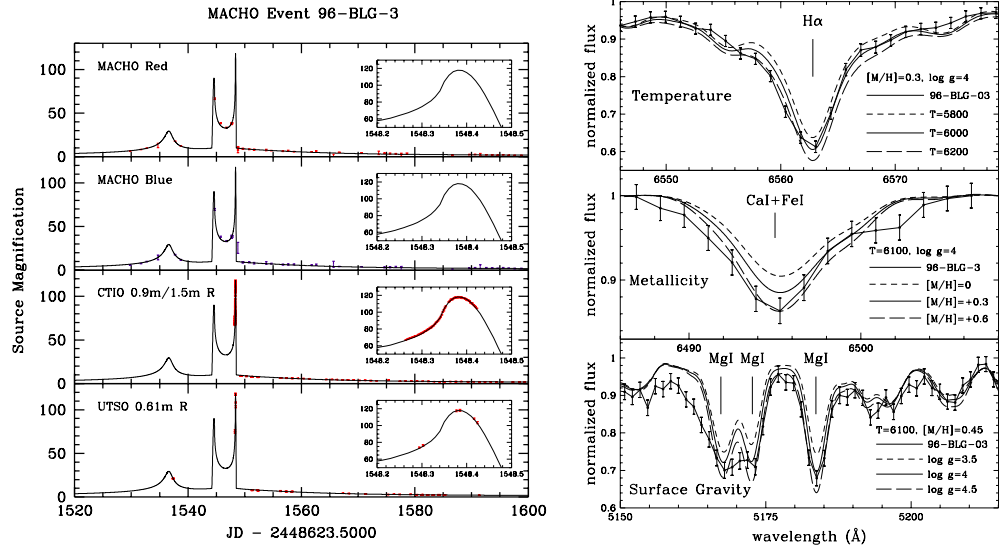


Figure 1. The high signal-to-noise target-of-opportunity NTT spectra of a bulge G-dwarf (right, Lennon et al. 1996) were made possible by multi-site photometric monitoring by GMAN and an accurate prediction for the time of the caustic crossing (left, Alcock et al. 2000).

2.1. Learning about the Source: Abundances and Limb-Darkening

Microlensing not only magnifies, but — if the caustic structure¹ from a multiple lens passes over the background star — actually *differentially* magnifies and thus spatially resolves its stellar source. This makes microlensing an excellent high-magnification, high-resolution (though impossible to point!) telescope with which to study faint and distant sources.

Microlens telescopes have been used to acquire spectra of subgiant and dwarf stars in the Galactic bulge that are too faint and crowded to be studied in other way, thereby allowing age and metallicity determinations for some of the oldest stars in the center of our Galaxy (Lennon et al., 1997). Real-time alerts of impending caustic crossings can be a boon to such work. For example, the GMAN caustic alert for MACHO 96-BLG-3 (Alcock et al., 2000) allowed Lennon et al. (1996) to measure the effective temperature, gravity and metallicity of the G-dwarf bulge source star; with the caustic boost, the NTT momentarily had the collecting power of a 17.5m telescope (Fig. 1). A relatively modest factor of three microlensing boost aided Minniti et al. (1998) to use the Keck to detect lithium in the turn-off source star of a different bulge event.

When a background star is transited by a caustic, the cool limb of the star will be magnified differentially during ingress and egress. This effect can be used

¹Caustics are sets of closed curves connecting positions in the source plane for which the determinant of the Jacobian lens mapping is zero. Since the magnification is inversely proportional to the determinant, a source crossed by a caustic will experience exceedingly high magnification, which is finite thanks only to the finite size of the source itself.

to resolve the surface brightness profile of the source, yielding a limb-darkening measurement that can be checked against predictions from stellar atmospheric models. Except for the Sun and a few nearby super giants, such measurements are difficult to obtain any other way.

Round-the-clock monitoring of binary event MACHO 97-BLG-28 allowed the PLANET team to fulfill this scientific potential for the first time. Data spaced by 3-30 minutes over the caustic peak allowed the slope change during the transit to be determined accurately, from which I- and V-band limb-darkening coefficients were derived directly without knowledge of the absolute stellar size (Fig. 2). The inferred surface brightness profile for the K-giant source star was consistent with stellar atmosphere models in both bands (Albrow et al. 1999b). An analysis of the binary microlensing event MACHO 98-SMC-1 using data from five microlensing teams has produced limb-darkening coefficients for an A-dwarf source star in three passbands (Afonso et al. 2000). This SMC star has an angular radius of only ~ 80 nanoarcseconds. No appropriate atmospheric models could be found for comparison. As expected, the A-dwarf is less limb-darkened than the K-giant, and limb darkening is less pronounced in redder passbands (Fig. 2). Limb-darkening measurements can be expected at the rate of $\gtrsim 2$ per year; PLANET has at least two suitable light curves from its 1999 season.

These first studies show that microlensing can be used effectively to boost the signal and resolution of our earth-bound telescopes. Since caustic structure is observed in $\sim 10\%$ of all microlensing events, and the approximate timing of a caustic crossing is often known a few days in advance, the primary hurdle will be re-assignment of telescope time on short-time scales for follow-up studies. Facilities that are flexible enough will be rewarded not only with more discoveries like these but also — as many of the contributions at this meeting have shown — the possibility to study stellar spots, rotation, and polarization, or even resolve quasar sizes and the atmospheric line structure of background source stars.

2.2. Learning about the Lens: Kinematics and Companions

If the nature of the background source is sufficiently well-understood (or irrelevant), a light curve generated by a caustic passing near the source can be used to learn about the lens responsible for the caustic structure. In good circumstances, three quantities can be determined: ρ_* , the size of the source star in units of the angular Einstein ring radius θ_E ($\theta_E \equiv \sqrt{4GM(D_S - D_L)/(c^2 D_S D_L)}$ for a lens of mass M a distance D_L from the observer and $D_S - D_L$ from the source); b , the instantaneous separation of a static binary lens in units of θ_E ; and q , the mass ratio of the binary. If either the Earth or the binary lens executes a significant fraction of its orbit during the duration of the microlensing event, gentle light curve anomalies may yield additional kinematic information (eg., Alcock et al. 1995). However, by using the stellar radius as a micro ruler and a caustic transit as a micro clock, the relative proper motion μ_{LS} between source and lens can sometimes be determined even in short duration events.

This possibility prompted five different teams (Afonso et al. 1998, Udalski et al. 1998, Albrow et al. 1999a, Alcock et al. 1999, Rhie et al. 1999) to monitor the rare binary microlensing event MACHO 98-SMC-01 in the direction of the Small Magellanic Cloud (SMC). The time taken by the SMC source star to cross the line caustic could be measured directly from the caustic peak portion

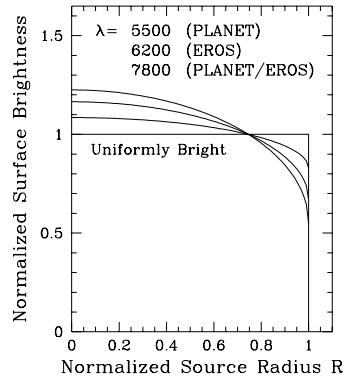
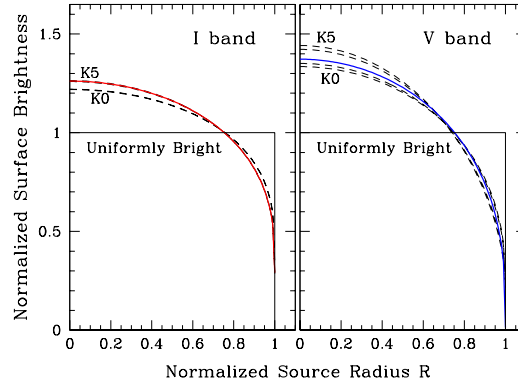


Figure 2. *Left:* The limb-darkened profiles reconstructed from PLANET light curve data (Albrow et al. 1999b) for MACHO 97-BLG-28 (solid lines) are consistent with stellar atmosphere models (dashed lines) for the K2 giant source star. *Right:* Reconstructed stellar profiles in three passbands (lowest curve at star's center is reddest) for the metal-poor A-dwarf source of MACHO 98-SMC-1 (Afonso et al. 2000).

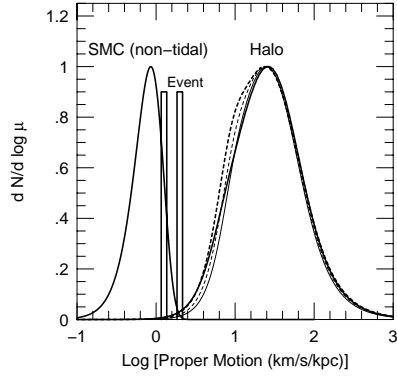
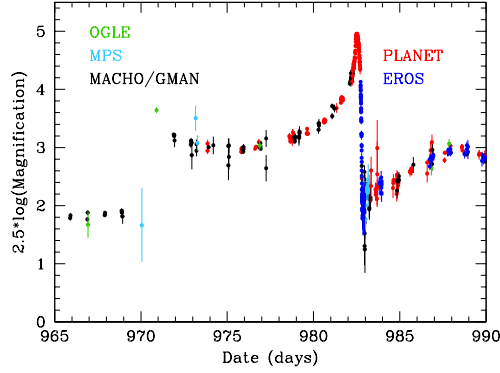


Figure 3. The light curve of MACHO 98-SMC-01 (left) combines data from five microlensing teams. Dense sampling by PLANET and EROS over the second peak produced the limb-darkening measurements of Fig. 2. Data from MACHO/GMAN, MPS and OGLE near the first peak ruled out the higher μ_{LS} model of PLANET (right, Albrow et al. 1999a), securing the result that its relative proper motion places the lens in the SMC, not the Galactic dark halo.

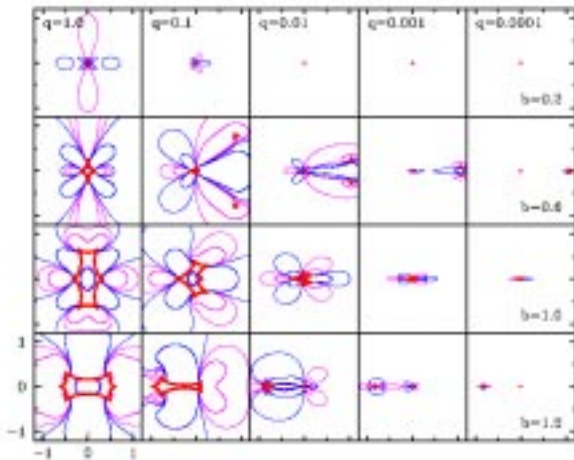


Figure 4. Contours of excess magnification ($\pm 1\%$, $\pm 5\%$, bold = ∞ = caustics) for binary lenses of different mass ratio q and separation b . Light curves of background point sources with trajectories crossing these contours will deviate from that of a single lens by the indicated amount. Distances are in θ_E . Adapted from Gaudi & Sackett (2000).

of the light curve. The rest of the light curve yielded the angle between source trajectory and caustic, allowing computation of the time t_* taken by the source to traverse a distance equal to its own radius. When combined with the angular stellar diameter θ_* estimated from spectral typing or color-surface brightness relations, the relative lens-source proper motion $\mu_{LS} \equiv \theta_*/t_*$ was determined. A joint analysis (Afonso et al. 2000) has confirmed the independent conclusions of all five groups that the lens proper motion is too small to have the halo-like kinematics expected for Galactic dark matter (Fig. 3), but is quite reasonable for a normal stellar binary lens residing in the SMC itself. More binary events in the direction of the Clouds must be studied in order to determine whether this conclusion is representative of the whole class, which would cast doubt on the notion that microlenses constitute a major fraction of the Galactic dark matter.

Although some binary light curves do not allow a unique determination of the angular separation b and mass ratio q , in most well-sampled cases categorization into stellar ($q \gtrsim 0.1$) or planetary ($q \lesssim 0.01$) companions can be made easily. (Note that the mass of Jupiter $M_J \approx 0.001 M_\odot$.) As Fig. 4 shows, for stellar lensing binaries of moderate separations ($0.5 \lesssim b \lesssim 1.5$), nearly all source trajectories inside θ_E will produce light curve anomalies at the $> 1\%$ level. Many stellar binaries have been detected in this way. In other microlensing events, the absence of detectable anomalies places strong constraints on the presence of lensing companions in this range of q and b .

To date, no clear planetary microlensing signatures have been detected. Generally, planets are difficult to rule out (or detect) because the regions of significant anomalous magnification are small. Nevertheless, a large class of massive planets have been ruled out in two high-magnification events that exhibited no large deviations. The MOA and MPS monitoring teams have excluded the presence of massive companions with $q > 0.001$ and $0.4 < b < 2.5$ in MACHO-

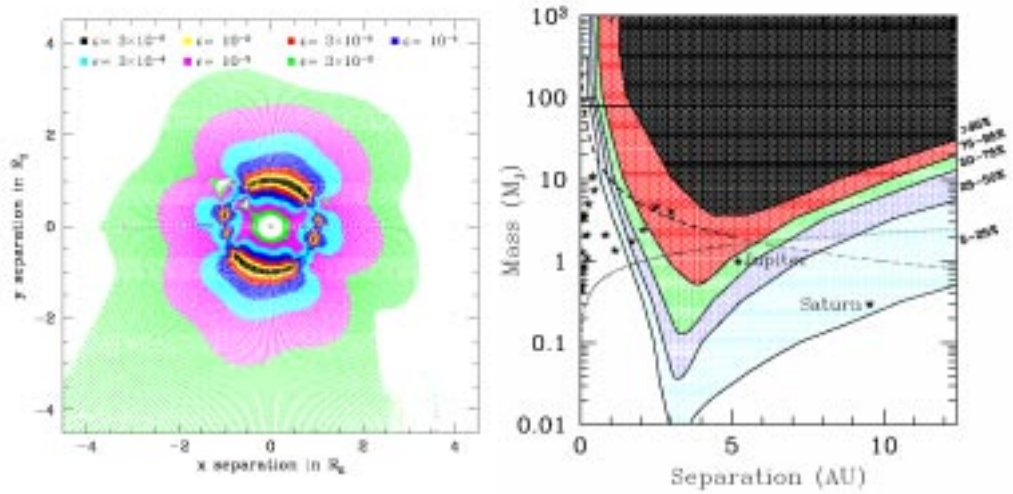


Figure 5. Exclusion diagrams for companions to two different microlenses. *Left:* Companions to MACHO 98-BLG-35 are excluded in the shaded regions (Rhie et al. 2000); the larger the mass ratio, the larger the excluded area on the sky. *Right:* Exclusion contours at various significance levels for OGLE-1998-BUL-14 companions of given mass and orbital radii, for a lens with $M = 1M_\odot$ and $D_L \theta_E = 3.1\text{AU}$ (Albrow et al. 2000a). Asterisks denote known radial velocity planets.

98-BLG-35 (Rhie et al. 2000). In this very high magnification event, companions with $q = 0.003$ were ruled out to ~ 3 Einstein radii (Fig. 5). The 600 data points collected by the PLANET team for OGLE-98-BUL-14 excluded companions with $q > 0.01$ over $0.4 < b < 2.4$ (Albrow et al. 2000a).

Assuming reasonable microlens characteristics, the exclusion (and detection) regime of microlensing extends to higher orbital separation than that of the radial velocity method (right panel, Fig. 5). Microlensing is also capable of detecting planets of smaller mass ratio, although care must be taken to remove systematic effects such as variable seeing (Albrow et al. 2000a), since perturbations caused by low-mass ($q < 0.001$) planets typically will be mild and short-lived. Microlensing is thus an excellent complement to Doppler searches for extra-solar planets in the Galaxy. A very preliminary statistical analysis of several light curves from the 1998 PLANET data set indicates that $\sim 25\%$ of all lenses do not have companions with mass $\gtrsim 5 M_J$ orbiting within an annulus bounded by $\sim 1 - 6$ AU (Gaudi et al. 1999, this meeting). For orbital radii close to the Einstein ring (~ 2.5 AU), this excluded fraction rises to $\sim 50\%$. Considerably tighter constraints on the presence of Jovian planets orbiting stellar microlenses are expected when analysis of the full PLANET data set is complete.

2.3. Auxiliary and Serendipitous Science: Variables and GRB

The frequent, high-precision photometry of dense fields required of intense microlensing monitoring is ideally suited for the study of rare, faint, short-period, or low-amplitude variable stars. The PLANET collaboration has discovered Bulge

variables as faint as $I = 19$, as rapidly-varying as once per 2 hours, and as subtle as 0.04 mag in total amplitude (Albrow et al. 2000b). The global, rapid-response nature of the monitoring networks can be used for target-of-opportunity studies of rare, irregular variables such as fading gamma ray bursts (GRBs). PLANET photometry produced precise optical positions for GRB 990510 (Vreeswijk et al. 1999) and GRB 990712 (Bakos et al. 1999), enabling VLT spectroscopy hours later that yielded redshifts for both bursts.

3. The Best is Yet to Come

Due to its limited scope, this review has centered only on the observational rewards reaped by the global networks that stand watch 24 hours a day monitoring microlensing events for light curve anomalies. It is the theorists, however, who have led the way, with ideas often thought to be far-fetched when proposed, yet verified a few short years later. If recent history is any guide, boldness of vision combined with care in execution will continue to serve theorist and observer alike in this young and rapidly evolving field of astrophysics.

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